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Effect of velocity loss during squat training on neuromuscular performance

David Rodríguez-Rosell[1,2] | **Juan Manuel Yáñez-García**[1,2] | **Ricardo Mora-Custodio**[1,2] | **Luis Sánchez-Medina**[3] | **Juan Ribas-Serna**[4] | **Juan José González-Badillo**[1]

[1]Physical Performance & Sports Research Center, Universidad Pablo de Olavide, Seville, Spain

[2]Department of Sport and Computer Science, Universidad Pablo de Olavide, Seville, Spain

[3]Center for Studies, Research and Sports Medicine, Instituto Navarro del Deporte (IND), Pamplona, Spain

[4]Department of Medical Physiology and Biophysics, University of Seville, Seville, Spain

Correspondence
David Rodríguez-Rosell, Physical Performance & Sports Research Center, Universidad Pablo de Olavide, Ctra. de Utrera, km 1, 41013 Seville, Spain.
Email: drodros@upo.es

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This study aimed to compare the effects of three resistance training (RT) programs differing in the magnitude of velocity loss (VL) allowed in each exercise set: 10%, 30%, or 45% on changes in strength, vertical jump, sprint performance, and EMG variables. Thirty-three young men were randomly assigned into three experimental groups (VL10%, VL30%, and VL45%; $n = 11$ each) that performed a velocity-based RT program for 8 weeks using only the full squat exercise (SQ). Training load (55–70% 1RM), frequency (2 sessions/week), number of sets (3), and inter-set recovery (4 min) were identical for all groups. Running sprint (20 m), countermovement jump (CMJ), 1RM, muscle endurance, and EMG during SQ were assessed pre- and post-training. All groups showed significant (VL10%: 6.4–58.6%; VL30%: 4.5–66.2%; VL45%: 1.8–52.1%; $p < 0.05$–0.001) improvements in muscle strength and muscle endurance. However, a significant group × time interaction ($p < 0.05$) was observed in CMJ, with VL10% showing greater increments (11.9%) than VL30% and VL45%. In addition, VL10% resulted in greater percent change in sprint performance than the other two groups (VL10%: −2.4%; VL30%: −1.8%; and VL45%: −0.5%). No significant changes in EMG variables were observed for any group. RT with loads of 55–70% 1RM characterized by a low-velocity loss (VL10%) provides a very effective and efficient training stimulus since it yields similar strength gains and greater improvements in sports-related neuromuscular performance (jump and sprint) compared to training with higher velocity losses (VL30%, VL45%). These findings indicate that the magnitude of VL reached in each exercise set considerably influences the observed training adaptations.

KEYWORDS

athletic performance, electromyography, muscle adaptations, muscle strength, neuromuscular fatigue, velocity-based resistance training

1 | INTRODUCTION

In addition to initial strength level,[1,2] training status,[3,4] and genetics,[5] the effectiveness of resistance training (RT) depends on an appropriate program design.[6] One of the permanent objectives of coaches and scientists is to find out what is the most time-efficient dose of exercise necessary to elicit optimal strength adaptations.[7] In this regard, recent research has focused on analyzing the dose-response relationship during RT in both young and older participants,[8–10] with particular attention to the effect of training volume due to the implications that this variable has on strength, hypertrophy, and neural adaptations.[6,11] Previous studies have suggested the existence of an inverted-U-shape relationship between training volume and performance.[9,10,12] This hypothesis has been derived from applying nonlinear mathematical models to the results obtained in previous research or meta-analyses.[9,10,12] However, few experimental studies have focused on solving this question, with particular attention to the number of repetitions performed in each training set.

The effect of manipulating the number of repetitions actually performed in each set with respect to the maximum number that can be completed against a given load corresponds to the so-called "level of effort"[13–15] which, according to an increasing body of research,[16-19] has revealed as a key factor in determining the acute responses[14,20,21] and subsequent adaptations to RT.[17,22,23] This concept has long been overlooked due to the assumption that RT should be conducted to the point of muscle failure in order to maximize gains in strength and muscle mass.[6] However, recent studies[16,18,19,23] and meta-analyses[24–26] suggest that training to failure may not produce superior strength gains and is perhaps counterproductive since it can induce a fast-to-slow phenotypic remodeling in muscle fiber type, which is not desirable for competitive sports where high-speed, "explosive" actions are decisive for performance.[17,18,23] Thus, although recent research seems to suggest not exercising to failure,[16,18,23] the optimal level of effort to be reached under different loading conditions for achieving certain training goals is still unclear.

Monitoring the loss of repetition velocity reached in each set serves as a very precise and practical method to quantify the level of effort incurred during RT.[13–15] As a consequence of recent advancements in technology, this velocity monitoring can provide real-time feedback to athletes during training. Thus, recent studies using velocity-based RT approaches have analyzed the effects of training with different magnitudes of velocity loss (VL) during each set in the squat,[17,18,23] bench press,[22,27] and pull-up[28] exercises. Specifically, studies using the full or deep squat have compared the mechanical and physiological changes induced by RT with different VL against a range of relative loads (70–85% 1RM). In brief, it was found that higher VL (>20%) maximized hypertrophic adaptations and induced greater increments in anabolic hormones (GH and IGF-1) but resulted in a significant reduction in the IIX muscle fiber phenotype,[17,18,23] whereas lower VL (≤ 20%) resulted in similar or even greater improvements in muscle strength, muscle endurance as well as in short-duration and high-speed actions such as vertical jumping and sprint running.[17,18,23] These gains in physical performance obtained by the lower VL groups were accompanied by an increase in electromyographic (EMG) activity of quadriceps femoris (*vastus medialis* and *vastus lateralis*) and lower chronic muscle damage.[17,18] In addition, Rodríguez-Rosell et al.[17] found a curvilinear relationship between VL in the set and percent changes from pre- to post-training in several selected strength variables as well as the countermovement jump (CMJ), so that the 10% and 20% VL groups obtained the greatest percent improvements but, once the 20% VL value was exceeded (30% and 40% VL groups), considerably lower changes were observed (see figure 3 in Rodríguez-Rosell et al.[17]). These findings appear to confirm the hypothesis proposed by other authors.[10,12]

Therefore, the results of these previous studies[17,18,23] seem to provide relevant information concerning the minimum dose of resistance exercise required to induce physical performance improvements and, consequently, to design more efficient RT programs. However, a limitation to consider is the relatively limited range of loads (70–85% 1RM) used in those studies. Since RT using different relative loads could lead to distinct neuromuscular adaptations, it appears that further research is needed to elucidate the adaptations brought about by RT programs that establish different VL limits against other commonly used load ranges. In this regard, although previous research[29,30] has shown no differences in strength gains when using different relative loads, it appears that moderate loads (50–70% 1RM) may constitute a more effective stimulus than heavy loads (>80% 1RM) for inducing increments in jumping and sprinting performance,[31–33] which could be more beneficial for improving performance in different sports modalities. Thus, the aim of the present study was to compare the effects of three RT programs in which medium loads (55–70% 1RM) and different VL limits (10%, 30%, and 45%) were used on changes in strength, physical performance (jumping and sprinting ability), and EMG variables.

2 | MATERIALS AND METHODS

2.1 | Participants

Thirty-six young men volunteered to take part in this study. Participants were physically active sports science students with RT experience ranging from 1 to 3 years (1–3 sessions per week), which had been injury-free for at least 6 months beforehand. After an initial evaluation, participants were matched according to their estimated one-repetition maximum (1RM) in the full squat (SQ) exercise (explained below) and then randomly assigned into three groups depending on the magnitude of VL to be allowed during each training set: 10% (VL10%, n = 12), 30% (VL30%, n = 12), or 45% (VL45%, n = 12). As a result of injury or illness not related to the training intervention, one participant from each group was excluded from the study. Thus, 11 participants in the VL10% group (age: 22.8 ± 3.9 years, body mass: 70.7 ± 5.1 kg, height: 1.76 ± 0.04 m), VL30% group

(21.9 ± 2.3 years, 73.7 ± 9.4 kg, 1.76 ± 0.07 m), and VL45% group (21.6 ± 2.8 years, 72.1 ± 9.6 kg, 1.72 ± 0.08 m) remained for analysis. No physical limitations, health problems, or musculoskeletal injuries that could affect testing were reported before the start of the investigation. The study was conducted according to the Declaration of Helsinki and was approved by the local ethics committee. After being informed of the purpose and experimental procedures, the participants signed a written informed consent form prior to participation.

2.2 | Experimental design

A longitudinal experimental study was designed to compare the changes on selected strength, physical performance, and muscle EMG variables following three RT programs which differed only in the percentage of VL allowed in each set: 10% versus 30% versus 45%. For this purpose, each group trained twice a week (with 72 h rest between sessions) during an 8-week period, using only the SQ exercise. All groups trained using the same relative loads, frequency, and rest periods between sets and sessions. All training and testing sessions were conducted in a research laboratory under the direct supervision of the investigators and under controlled environmental conditions (~20°C and ~60% humidity). Each participant trained on the same weekdays (either Monday and Thursday or Tuesday and Friday) and at the same time of the day (±1 h) to avoid possible interfering factors. Participants were required not to engage in any other type of strenuous physical activity, exercise training, or sports competition for the duration of the present investigation. All participants were assessed before (Pre) and after (Post) the 8-week training intervention using a battery of tests performed in two sessions separated by 24 h. The time elapsed between the Pre and the start of the training intervention and between the end of training and the Post was 96 h. The first session was used to conduct medical examinations and anthropometric measurements. The second testing session consisted of (a) 20 m all-out running sprint, (b) CMJ test, (c) a progressive loading test in the SQ exercise, and (d) a fatigue test, also in the SQ. During the progressive loading test, the EMG response of *vastus lateralis* (V_{LA}) and *vastus medialis* (V_{ME}) muscles was recorded. Training compliance was 100% for all groups. Exactly the same testing protocol (described below) was carried out during both pre- and post-testing sessions.

2.3 | Testing procedures

Before the physical performance assessment, participants carried out a general standardized warm-up consisting of 5 min of running at a self-selected easy intensity, 5 min of joint mobilization exercises, followed by three sets of progressively faster 30 m running accelerations. At least three experienced researchers supervised the testing sessions to ensure that correct and consistent techniques were used during all tests. Strong verbal encouragement was provided during all tests to motivate participants to give a maximal effort. The SQ exercise was performed on a Smith machine (Multipower Fitness Line, Peroga, Murcia, Spain) in all testing and training sessions.

2.3.1 | Running sprint test

Participants carried out two maximal 20 m running sprints (3 min rest) on a synthetic indoor running track, with the fastest of both attempts kept for analysis. The specific warm-up protocol consisted of one 40 m sprint at 80% of maximal individual perceived effort, two 30 m sprints at 90% of maximal effort, and one 20 m sprint at maximal effort. Photocell timing gates (Witty wireless training timer, Microgate, Bolzano, Italy) were set up at a height of 1.10 m above ground level and placed at 0, 10, and 20 m so that the times to cover 0–10 m (T10) and 0–20 m (T20) could be determined. A standing start with the lead-off foot placed 1 m behind the starting timing gate was used. The coefficients of variation (CV) for test-retest reliability for T10 and T20 were 1.9% and 1.0%, respectively. The intraclass correlation coefficients (ICC) were 0.92 (95% confidence interval, CI: 0.84–0.96) for T10 and 0.96 (95% CI: 0.93–0.98) for T20.

2.3.2 | Countermovement jump test

The CMJ was performed with the subject standing in an upright position with the hands placed on the hips to avoid arm swings. A fast downward movement (knee flexion) was immediately followed by a fast upward vertical movement (knee extension) with the goal of jumping as high as possible, all in one sequence. Participants completed five trials, with a 45 s rest in-between. The highest and lowest values were discarded, and the resulting mean kept for analysis.[17,18,23,34] CMJ height was calculated from flight time using an infrared timing system (Optojump Next, Microgate, Bolzano, Italy). The specific warm-up consisted of two sets of 10 bodyweight squats (2 min rest), five CMJs at progressive intensity (20 s rest), and three maximal CMJs (30 s rest). The CV was 1.4%, and the ICC was 0.99 (95% CI: 0.99–1.00).

2.3.3 | Progressive loading test in the SQ exercise

A detailed description of the SQ testing protocol has been provided elsewhere.[35] The participants performed the SQ

TABLE 1 Descriptive characteristics of the squat training program performed by the VL10%, VL30% and VL45% groups

Scheduled	Session 1	Session 2	Session 3	Session 4	Session 5	Session 6	Session 7	Session 8	Session 9
Sets × Velocity Loss (%)									
VL10%	3 × 10%	3 × 10%	3 × 10%	3 × 10%	3 × 10%	3 × 10%	3 × 10%	3 × 10%	3 × 10%
VL30%	3 × 20%	3 × 30%	3 × 30%	3 × 30%	3 × 30%	3 × 25%	3 × 30%	3 × 30%	3 × 30%
VL45%	3 × 20%	3 × 35%	3 × 45%	3 × 45%	3 × 45%	3 × 35%	3 × 45%	3 × 45%	3 × 45%
Target MPV ($m \cdot s^{-1}$)	1.08	1.08	1.08	1.08	1.08	1.00	1.00	1.00	1.00
	(~55% 1RM)	(~55% 1RM)	(~55% 1RM)	(~55% 1RM)	(~55% 1RM)	(~60% 1RM)	(~60% 1RM)	(~60% 1RM)	(~60% 1RM)
Actually performed									
Velocity Loss (%)									
VL10%	10.6 ± 0.8	9.4 ± 1.1	10.5 ± 1.0	11.1 ± 1.6	11.1 ± 1.4	11.5 ± 2.2	10.6 ± 1.6	10.9 ± 1.7	11.3 ± 2.1
VL30%	20.4 ± 1.9*	29.6 ± 2.4*	29.4 ± 1.3*	29.2 ± 1.1*	31.2 ± 2.0*	28.1 ± 3.6*	30.4 ± 2.4*	30.5 ± 2.3*	29.7 ± 1.5*
VL45%	20.0 ± 1.9*	34.3 ± 1.6*,†	45.1 ± 2.1*,†	43.4 ± 2.0*,†	45.0 ± 2.5*,†	35.5 ± 2.5*,†	44.7 ± 2.2*,†	44.9 ± 1.8*,†	44.5 ± 2.2*,†
Reps per set									
VL10%	5.0 ± 1.4	4.5 ± 1.1	4.9 ± 1.2	5.3 ± 1.4	4.8 ± 1.1	4.0 ± 0.8	4.2 ± 0.9	3.9 ± 0.4	3.8 ± 0.6
VL30%	8.1 ± 1.7*	9.4 ± 2.1*	10.7 ± 3.5*	10.9 ± 2.7*	10.5 ± 2.9*	7.8 ± 1.7*	7.9 ± 1.4*	7.5 ± 1.5*	7.2 ± 1.3*
VL45%	8.6 ± 2.1*	14.0 ± 3.2*,†	15.5 ± 3.9*,†	15.0 ± 3.4*,†	13.9 ± 2.9*,†	10.9 ± 2.8*,†	11.4 ± 3.0*,†	11.6 ± 4.1*,†	11.1 ± 3.5*,†
MPV_{BEST} ($m \cdot s^{-1}$)									
VL10%	1.09 ± 0.02	1.09 ± 0.03	1.09 ± 0.03	1.10 ± 0.03	1.08 ± 0.02	1.01 ± 0.02	1.01 ± 0.02	1.01 ± 0.03	1.00 ± 0.02
	(~54.4% 1RM)	(~53.9% 1RM)	(~54.1% 1RM)	(~53.8% 1RM)	(~54.5% 1RM)	(~59.4% 1RM)	(~59.2% 1RM)	(~59.5% 1RM)	(~59.9% 1RM)
VL30%	1.08 ± 0.02	1.09 ± 0.03	1.09 ± 0.02	1.09 ± 0.03	1.09 ± 0.03	1.02 ± 0.03	1.01 ± 0.02	1.02 ± 0.02	1.01 ± 0.02
	(~54.6% 1RM)	(~53.7% 1RM)	(~54.3% 1RM)	(~54.1% 1RM)	(~54.1% 1RM)	(~58.9% 1RM)	(~59.4% 1RM)	(~59.0% 1RM)	(~59.4% 1RM)
VL45%	1.09 ± 0.04	1.09 ± 0.03	1.08 ± 0.03	1.09 ± 0.02	1.08 ± 0.03	1.02 ± 0.02	1.00 ± 0.02	1.01 ± 0.03	1.02 ± 0.02
	(~53.2% 1RM)	(~54.2% 1RM)	(~54.8% 1RM)	(~54.4% 1RM)	(~54.6% 1RM)	(~59.1% 1RM)	(~60.2% 1RM)	(~59.3% 1RM)	(~58.8% 1RM)

Scheduled	Session 10	Session 11	Session 12	Session 13	Session 14	Session 15	Session 16
Sets × Velocity Loss (%)							
VL10%	3 × 10%	3 × 10%	3 × 10%	3 × 10%	3 × 10%	3 × 10%	3 × 10%
VL30%	3 × 30%	3 × 30%	3 × 30%	3 × 30%	3 × 30%	3 × 30%	3 × 30%
VL45%	3 × 45%	3 × 45%	3 × 45%	3 × 45%	3 × 45%	3 × 45%	3 × 45%

(Continues)

TABLE 1 (Continued)

Scheduled	Session 10	Session 11	Session 12	Session 13	Session 14	Session 15	Session 16	
Target MPV ($m \cdot s^{-1}$)	0.92	0.92	0.92	0.92	0.84	0.84	0.84	
	(~65% 1RM)	(~65% 1RM)	(~65% 1RM)	(~65% 1RM)	(~70% 1RM)	(~70% 1RM)	(~70% 1RM)	
Actually performed								**Overall**
Velocity Loss (%)								
VL10%	10.6 ± 2.5	10.8 ± 1.5	11.7 ± 2.2	11.9 ± 2.7	11.3 ± 2.6	10.8 ± 2.3	11.1 ± 1.2	10.9 ± 1.8
VL30%	32.0 ± 3.5*	31.4 ± 3.7*	30.6 ± 3.3*	31.4 ± 1.8*	32.1 ± 2.3*	31.6 ± 3.0*	30.1 ± 1.8*	29.8 ± 3.6*
VL45%	44.7 ± 2.6*,†	45.3 ± 4.0*,†	45.9 ± 2.7*,†	44.9 ± 2.6*,†	46.4 ± 2.2*,†	45.1 ± 2.3*,†	44.3 ± 3.1*,†	42.1 ± 7.0*,†
Reps per set								
VL10%	3.4 ± 0.6	3.3 ± 1.0	3.1 ± 0.5	3.1 ± 0.8	2.5 ± 0.6	2.4 ± 0.6	2.2 ± 0.5	3.8 ± 1.3
VL30%	6.1 ± 1.3*	5.6 ± 1.6*	5.7 ± 1.2*	5.9 ± 0.8*	4.4 ± 0.8*	4.3 ± 1.4*	4.1 ± 1.2*	7.2 ± 2.8*
VL45%	8.6 ± 2.6*,†	8.8 ± 2.7*,†	8.7 ± 2.2*,†	8.1 ± 1.9*,†	6.5 ± 1.7*,†	7.1 ± 1.9*,†	7.5 ± 2.1*,†	10.4 ± 3.9*,†
MPV_{BEST} ($m \cdot s^{-1}$)								
VL10%	0.92 ± 0.03	0.93 ± 0.02	0.93 ± 0.01	0.93 ± 0.02	0.85 ± 0.02	0.85 ± 0.02	0.83 ± 0.02	0.99 ± 0.09
	(~65.0% 1RM)	(~64.2% 1RM)	(~64.8% 1RM)	(~64.5% 1RM)	(~69.2% 1RM)	(~69.5% 1RM)	(~70.9% 1RM)	(~61.1% 1RM)
VL30%	0.92 ± 0.02	0.94 ± 0.02	0.93 ± 0.02	0.92 ± 0.01	0.84 ± 0.03	0.85 ± 0.03	0.85 ± 0.02	0.99 ± 0.09
	(~65.3% 1RM)	(~63.9% 1RM)	(~64.1% 1RM)	(~65.1% 1RM)	(~69.8% 1RM)	(~69.4% 1RM)	(~69.0% 1RM)	(~60.9% 1RM)
VL45%	0.94 ± 0.02	0.93 ± 0.03	0.92 ± 0.03	0.92 ± 0.02	0.84 ± 0.03	0.85 ± 0.03	0.84 ± 0.02	0.99 ± 0.09
	(~63.9% 1RM)	(~64.6% 1RM)	(~65.4% 1RM)	(~65.4% 1RM)	(~70.3% 1RM)	(~69.6% 1RM)	(~70.1% 1RM)	(~61.1% 1RM)

Note: Data are mean ± SD. Only one exercise (full squat) was used in training. The groups (n = 11 each) trained with different percent velocity loss (VL) in each set: 10% (VL10%), 30% (VL30%) and 45% (VL45%). MPV: mean propulsive velocity attained against the intended load (%1RM); Reps: number of repetitions performed; MPV_{BEST}: mean propulsive velocity of the fastest (usually first) repetition in the first set. The actual velocity losses reported are the mean of the three sets. Statistically significant differences with respect to: *VL10% ($p < 0.05$); †VL30% ($p < 0.05$).

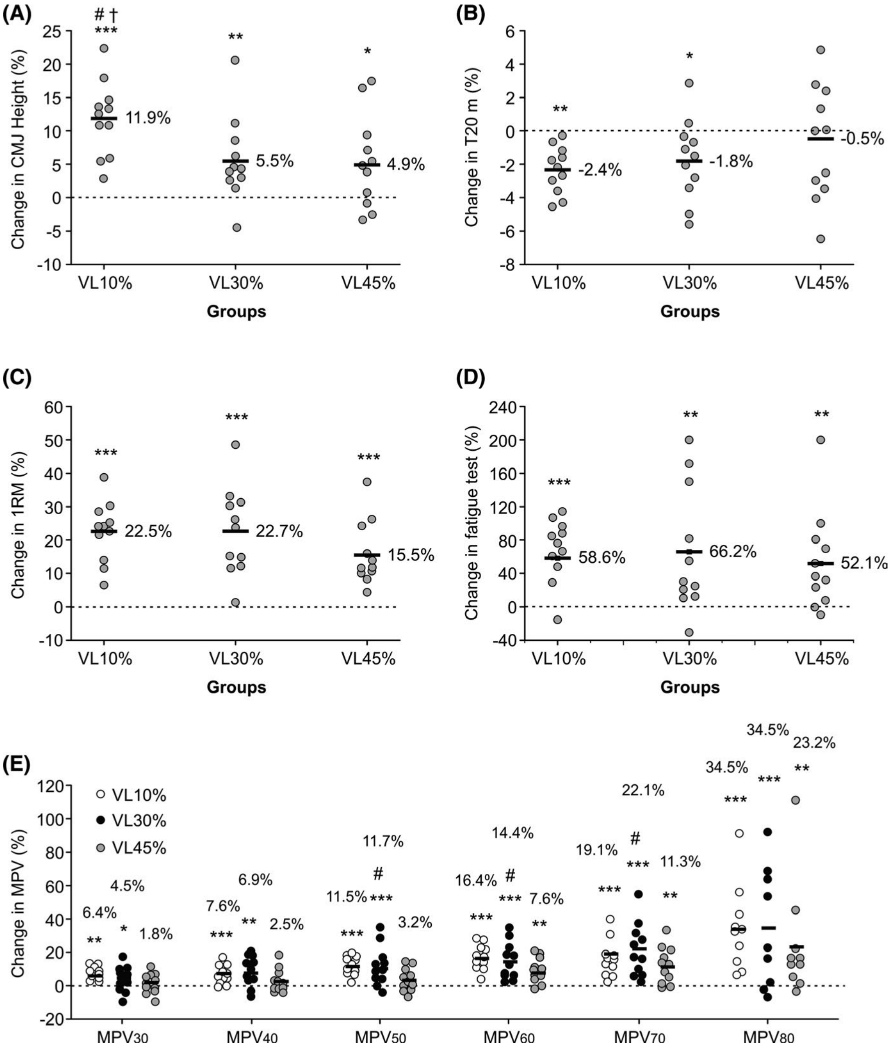

FIGURE 1 Individual and average percent change in selected neuromuscular performance variables: CMJ (A), 20 m sprint time (B), estimated 1RM (C), fatigue test (D) and velocity attained against different absolute loads (30–80 kg) in the full squat exercise (E) for the VL10%, VL30%, and VL45% groups. Statistically significant "time × group" interaction: #$p < 0.05$. Statistically significant differences with respect to VL45% $^{\dagger}p < 0.05$. Intra-group significant differences from Pre to Post: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

from an upright position, descending (eccentric phase) in a continuous motion until the posterior thighs and calves made contact with each other, then immediately reversed motion and ascended back to the starting position. The eccentric phase was performed at a controlled mean velocity (~0.50–0.60 $m \cdot s^{-1}$), whereas participants were required to always execute the concentric phase at maximal intended velocity. The specific warm-up consisted of two sets of 8 and 6 SQ repetitions (3 min rests) against loads of 20 and 30 kg, respectively. The initial load was set at 30 kg for all participants and was gradually increased by 10 kg until the mean propulsive velocity (MPV) was lower than ~0.60 $m \cdot s^{-1}$, which corresponds to ~85% 1RM in the SQ.[35] During the test, three repetitions were executed for light (MPV>1.10 $m \cdot s^{-1}$), two for medium (1.10 $m \cdot s^{-1}$>MPV>0.80 $m \cdot s^{-1}$), and only one for the heaviest (MPV<0.80 $m \cdot s^{-1}$) loads. Inter-set rests ranged from 3 min (light) to 5 min (heavy loads). A total of 7.4 ± 1.3 increasing loads were used for each participant. The exact same warm-up and progression of absolute loads were repeated in the post-test for each participant. Only the best repetition at each load, according to the criterion of fastest MPV, was considered for subsequent analysis. The following variables derived from this test were used for analysis: (a) the estimated 1RM was calculated for each participant from the MPV value attained against the heaviest load (kg) lifted in the progressive loading test, as follows: $(100 \times \text{load})/(-5.961 \times \text{MPV}^2) - (50.71 \times \text{MPV}) + 117$[35]; (b) average MPV attained against all absolute loads common to pre- and post-tests (AV); (c) average MPV against common loads that were lifted faster than 1.00 $m \cdot s^{-1}$ (AV>1); (d) average MPV against common loads lifted slower than 1.00 $m \cdot s^{-1}$ (AV<1); and (e) MPV against 30 kg (MPV_{30}), 40 kg (MPV_{40}), 50 kg (MPV_{50}), 60 kg (MPV_{60}), 70 kg (MPV_{70}), and 80 kg (MPV_{80}). These variables have been shown as highly reliable,[36,37] and they provide a much more comprehensive analysis of training-induced changes across the load(force)-velocity spectrum rather than simply focusing on a 1RM strength value. A linear velocity transducer (T-FORCE Dynamic Measurement System; Ergotech Consulting Ltd., Murcia, Spain) and its associated software (version 3.70) automatically calculated

TABLE 2 Changes in selected neuromuscular performance variables from pre- to post-training for each experimental group

	VL10%			VL30%			VL45%		
	Pre	Post	ES (±95% CI)	Pre	Post	ES (±95% CI)	Pre	Post	ES (±95% CI)
CMJ (cm) #	39.1 ± 5.7	43.8 ± 6.6***,†	0.75 ± 0.39	39.8 ± 4.7	41.8 ± 4.5**	0.44 ± 0.36	39.0 ± 6.3	40.8 ± 6.4*	0.29 ± 0.27
T10 (s)	1.77 ± 0.07	1.71 ± 0.06*	−0.89 ± 0.57	1.75 ± 0.09	1.73 ± 0.06	−0.38 ± 0.38	1.75 ± 0.12	1.75 ± 0.09	−0.03 ± 0.52
T20 (s)	3.06 ± 0.10	2.99 ± 0.08**	−0.80 ± 0.45	3.04 ± 0.15	2.98 ± 0.09*	−0.49 ± 0.29	3.05 ± 0.13	3.03 ± 0.13	−0.12 ± 0.46
1RM (kg)	96.1 ± 13.9	117.4 ± 17.7***	1.34 ± 0.66	97.4 ± 19.2	118.9 ± 22.6***	1.03 ± 0.55	96.8 ± 15.1	111.7 ± 19.2***	0.86 ± 0.47
AV ($m·s^{-1}$)	0.95 ± 0.04	1.10 ± 0.06***,†,‡	3.00 ± 1.40	0.98 ± 0.07	1.12 ± 0.10***	1.67 ± 0.96	0.97 ± 0.08	1.05 ± 0.10***	0.82 ± 0.46
AV >1 ($m·s^{-1}$)	1.25 ± 0.04	1.35 ± 0.06***,†,‡	2.14 ± 1.07	1.27 ± 0.07	1.37 ± 0.10***	1.08 ± 0.70	1.28 ± 0.06	1.30 ± 0.07	0.38 ± 0.56
AV <1 ($m·s^{-1}$)	0.67 ± 0.03	0.87 ± 0.06***	4.04 ± 1.90	0.71 ± 0.04	0.89 ± 0.11***	2.19 ± 1.11	0.67 ± 0.04	0.80 ± 0.08***	1.86 ± 0.99
Fatigue test (rep)	11.5 ± 3.5	17.6 ± 4.2***	1.59 ± 0.97	12.0 ± 4.3	17.6 ± 4.2**	1.34 ± 0.98	12.9 ± 6.0	18.3 ± 6.3**	0.87 ± 0.60

Note: Data are mean ± SD. The groups (n = 11 each) trained with different percent velocity loss (VL) in each set: 10% (VL10%), 30% (VL30%), and 45% (VL45%). Statistically significant "time × group" interaction: #$p < 0.05$. Statistically significant differences with respect to: VL30% ‡$p < 0.05$; VL45% †$p < 0.05$. Intra-group significant differences from Pre to Post: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Abbreviations: Pre: initial assessment; Post: final assessment; ES: intra-group effect size; CI: confidence interval; rep: number of repetitions performed; 1RM: estimated one-repetition maximum in the full squat exercise, CMJ: countermovement jump height, T10: 10 m sprint time, T20: 20 m sprint time; AV: average MPV attained against all absolute loads common to pre- and post-tests in the squat progressive loading test; AV >1: average MPV attained against common loads that were lifted faster than 1.00 $m·s^{-1}$, AV <1: average MPV against common loads lifted slower than 1.00 $m·s^{-1}$.

and registered the kinematics of every repetition and provided auditory and visual feedback. The transducer's wire cable was attached to the right side of the Smith machine's bar. Instantaneous vertical bar velocity was sampled at 1000 Hz. Recent studies have shown that this particular device is an extremely reliable technology for velocity-based training purposes, showing the finest readings among the tested devices along the entire spectrum of mean velocities (from 0.2 to 2.8 $m·s^{-1}$) compared to other position transducers, accelerometer-based units, or smartphone apps.[14,38,39]

2.3.4 | Fatigue test

After finishing the progressive loading test, and following a 5 min rest, a fatigue test was performed in the SQ. For each participant, this test was performed against an absolute load that elicited a MPV value of ~0.84 $m·s^{-1}$ (~70% 1RM) in the non-fatigued, pre-exercise, rested condition. Thus, before starting the test, adjustments in the load (kg) to be lifted were made when needed so that the velocity of the first repetition matched the required target MPV. The participants were required to lift the bar as fast as possible during the concentric phase of each repetition, from the first repetition until the point where MPV was lower than 0.50 $m·s^{-1}$ (Table S1). Performance in this test was determined as the total number of repetitions completed until the first repetition to fall below 0.50 $m·s^{-1}$ (included). In order to estimate muscle endurance, the fatigue test was performed against the same absolute load for each participant during both pre- and post-sessions. This procedure is mainly justified by the fact that sports performance is determined, to a large extent, by the ability of the athlete to move, displace or lift the same absolute load (either their own body weight and/or an external implement) at an increasing velocity or a greater number of times during the distance or time the event lasts. If the absolute load were modified in the Post, the change in performance could not be adequately assessed, since we could not know if the observed differences are due to a change in strength or to the change in the lifted load or resistance. This same procedure has been used in previous studies.[17,18,22]

2.3.5 | Knee extensor muscle activation

During the progressive loading test in the SQ exercise, EMG muscle activity was recorded from the V_{LA} and V_{ME} muscles of the right leg via pairs of bipolar surface electrodes (Blue Sensor N-00-S, Medicotest) with a distance between the electrodes' centers of 22 mm. After careful preparation of the skin by shaving and cleaning with alcohol, surface electrodes were placed over the belly of the muscle parallel to the presumed

TABLE 3 Pearson's correlation coefficients for relationships between individual relative changes in selected training and performance variables

Variables	T10	T20	1RM	AV	AV >1	AV <1	Fatigue test	MTV	Rep
CMJ	−0.678***	−0.723***	0.292	0.498**	0.465**	0.411*	0.232	0.691***	−0.644***
T10		0.883***	−0.425*	−0.412*	−0.279	−0.399*	−0.406*	−0.369*	0.398*
T20			−0.435*	−0.468**	−0.356*	−0.441*	−0.475**	−0.427*	0.444*
1RM				0.797***	0.602***	0.831***	0.712***	0.427*	−0.344
AV					0.912***	0.872***	0.546***	0.612***	−0.478**
AV >1						0.654***	0.364*	0.621***	−0.442*
AV <1							0.540***	0.521**	−0.432*
Fatigue test								0.144	−0.158
MTV									−0.854***

Abbreviations: 1RM: estimated one-repetition maximum strength in the full squat; CMJ: countermovement jump height; T10: 10 m sprint time; T20: 20 m sprint time; AV: average MPV attained against all absolute loads common to pre- and post-tests in the squat progressive loading test; AV >1: average MPV attained against common loads that were lifted faster than 1.00 $m{\cdot}s^{-1}$; AV <1: average MPV attained against common loads lifted slower than 1.00 $m{\cdot}s^{-1}$.; MTV: mean training velocity for all repetitions performed during training; Rep: total number of repetitions completed during the training program.

Statistically significant relationships: $*p < 0.05$, $**p < 0.01$, $***p < 0.001$. See text for further details.

orientation of the muscle fibers of V_{LA} and V_{ME}, according to Surface EMG for Non-Invasive Assessment of Muscles (SENIAM) guidelines.[40] All electrode positions were carefully measured for each participant and were marked with henna dye to ensure identical recording sites throughout the 8-week training period to ensure reliable placement of electrodes during testing sessions. The reference electrode was placed on the patella of the same limb. Skin-electrode impedance was assessed on each occasion to verify that it was maintained at a consistent level for each individual (within 0.5 MΩ) and at a value <5 MΩ for all participants. EMG signals were synchronized with kinematic data by recording at 1000 Hz with the same analogue-to-digital converter and PC. During off-line analysis, the signals were band-pass filtered in both directions between 6 and 500 Hz using a second-order Butterworth digital filter. The parameters analyzed in the present study corresponded to the first 500 ms of the concentric phase of the SQ exercise in both V_{ME} and V_{LA} muscles (Figure S1).[17] The EMG variables calculated were as follows: root mean square (RMS), median power frequency (F_{med}), and maximal power frequency (F_{max}). Reliability of these sEMG variables has recently been reported elsewhere.[41] EMG data were collected using LabChart software version 7.0 (National Instruments Corporation. Austin, TX, USA), and data analysis was performed off-line using the MATLAB 2011a software environment (MathWorks Inc., Natick, Massachusetts, USA). For comparison between pre- and post-tests, EMG values recorded against each absolute load (30, 40, 50, 60, 70, and 80 kg) were normalized to the respective maximal absolute load lifted during the corresponding progressive loading test. Thus, the EMG values corresponding to each load were expressed as percentages of the maximum load lifted in that same test. This normalization was done because absolute EMG values are significantly influenced by factors including the thickness of subcutaneous tissue, the electrode placement (site and orientation), and the method used to shave, abrade, and clean the surface of the skin. These factors can prevent a direct comparison between the values of the pre- and post-test.[40]

2.4 | Resistance training program

All participants carried out an 8-week velocity-based RT program involving two sessions per week (16 total sessions), using only the SQ exercise. Training variables including relative load (55–70% 1RM), number of sets (three), inter-set recovery (4 min), and recovery time between sessions (72 h) were identical for all three experimental groups. The only difference between groups was the percent VL allowed in each training set: 10% versus 30% versus 45%. Descriptive characteristics of the RT program are presented in Table 1. Relative load (% 1RM) for each traininor each training session was determined from theg session was determined from the load-velocity relationship for the SQ.[35] Thus, a target velocity to be attained in the first (usually the fastest) repetition of the first set of each training session was used as an estimation of load, as follows: ~1.08 $m{\cdot}s^{-1}$ (~55% 1RM), ~1.00 $m{\cdot}s^{-1}$ (~60% 1RM), ~0.92 $m{\cdot}s^{-1}$ (~65% 1RM), and ~0.84 $m{\cdot}s^{-1}$ (~70% 1RM). Consequently, before starting the first set, adjustments in the proposed load (kg) were made when needed so that the velocity of the first repetition matched the scheduled target MPV (±0.03 $m{\cdot}s^{-1}$). Once this individual load (kg) was determined, it was maintained for the three training sets for each participant. The volume (number of repetitions) to perform in each set was objectively determined by means of the magnitude (percentage) of VL reached [13] so that each set was terminated as soon as the prescribed VL limit was exceeded.[14,17,18,23] According to this method, and depending on the training group, participants performed repetitions until reaching 10%, 30%, or 45% VL with respect to the best (fastest) MPV of the set. For the VL10% group, the percent VL was 10% in all training sessions. However, for the other two groups, VL followed a progression from 20% to 30% for VL30% and from 20% to 45% for VL45%. Thus, the average VL during the training program were 29.8 ± 3.6% and 42.1 ± 7.0% for VL30% and VL45%, respectively (Table 1). This progression was used to avoid excessive overload and minimize the risk of injury at the beginning of the training program in these experimental groups. Repetitions for all participants and sessions were measured and recorded using the linear velocity transducer. Participants received immediate velocity feedback while being encouraged to perform each repetition at maximal intended velocity. Before all training sessions, participants carried out a general standardized warm-up consisting of 5 min of running at a self-selected easy intensity, 5 min of joint mobilization exercises, followed by 3 sets of progressively faster 30 m running accelerations. The specific warm-up was also the same for all groups and consisted of (1) one set of 6 repetitions against 50% 1RM for sessions 1–5; (2) two sets of 6 and 5 repetitions against 50% and 55% 1RM, respectively, for sessions 6–9; (3) two sets of 6 and 4 repetitions against 50% and 60% 1RM, respectively, for sessions 10–13; and (4) three sets of 6, 3 and 3 repetitions against 50%, 60% and 65% 1RM, respectively, for sessions 14–16. A 3-min rest between the SQ warm-up sets was always used.

2.5 | Statistical analysis

Standard statistical methods were used for the calculation of means, standard deviations (SD), and correlations. The normality of distribution of the variables at Pre was examined with the Shapiro-Wilk test, and the homogeneity of variance across groups (VL10% vs. VL30% vs. VL45%) was verified using Levene's test. A one-way random effects model (model 2,1) ICC with absolute agreement was used to determine relative reliability. Absolute reliability was reported using the CV. The training-related effects were assessed using a 3 (group: VL10% vs. VL30% vs. VL45%) × 2 (time: Pre vs. Post) factorial ANOVA with Bonferroni's adjustment. In addition, effect sizes (ES) were calculated using Hedge's g on the pooled SD.[42] Relationships between changes in selected variables were analyzed using Pearson's correlation coefficient (r). Statistical significance was accepted at $p < 0.05$. Null hypothesis tests were performed using SPSS software version 17.0 (SPSS, Chicago, IL).

3 | RESULTS

Data for all variables analyzed were homogeneous and normally distributed. No significant differences between groups (VL10% vs. VL30% vs. VL45%) were found at Pre for any of the variables analyzed. Descriptive characteristics of the training actually performed by each group are presented in Table S2, whereas changes in neuromuscular performance variables are displayed in Table 2.

3.1 | Training program

Both the fastest MPV of the first set (ie, that indicative of relative load, %1RM) and the actual average VL over three sets matched those scheduled for each training session. No significant differences between groups were observed for the fastest MPV of the first set in any session (Table 1). Overall, participants in the VL45% group performed significantly ($p < 0.001$) more repetitions (501.1 ± 106.8) than those in the VL10% (180.8 ± 29.0) and VL30% (347.9 ± 62.3) groups, whereas the VL30% group completed a greater number of repetitions ($p < 0.001$) than VL10% (Table S2). There were no significant differences between training groups in the number of repetitions completed at velocities faster than 0.90 $m \cdot s^{-1}$, whereas the number of repetitions performed at slower velocities (MPV <0.90 $m \cdot s^{-1}$) was progressively greater as VL increased, showing significant differences between VL10%, VL30%, and VL45%, respectively (Table S2). VL10% trained at a significantly faster ($p < 0.001$) mean velocity (0.91 ± 0.10 $m \cdot s^{-1}$) than VL30% (0.83 ± 0.13 $m \cdot s^{-1}$) and VL45% (0.76 ± 0.16 $m \cdot s^{-1}$), whereas mean training velocity for VL30% was faster ($p < 0.001$) compared to VL45%.

3.2 | Strength and physical performance (jumping and sprinting ability)

A significant "time × group" interaction ($p < 0.05$) was only found for CMJ (Table 2 and Figure 1). Between-group comparisons showed significantly ($p < 0.05$) greater changes from pre- to post-training for VL10% compared to VL30% and VL45% in AV and AV>1 (Table 2 and Figure 1). In addition, a statistically significant difference ($p < 0.05$) was found between VL10% and VL45% in CMJ. VL10% showed significant pre-post changes in all strength variables analyzed (8.5–28.6%; $p < 0.001$), fatigue test (58.6%; $p < 0.001$), CMJ (11.9%; $p < 0.001$) and sprint performance (−3.1 to −2.4%; $p < 0.05$–0.01). VL30% obtained significant improvements in all variables assessed ($p < 0.05$–0.001) except in T10 (−1.5%), whereas VL45% significantly improved in all variables

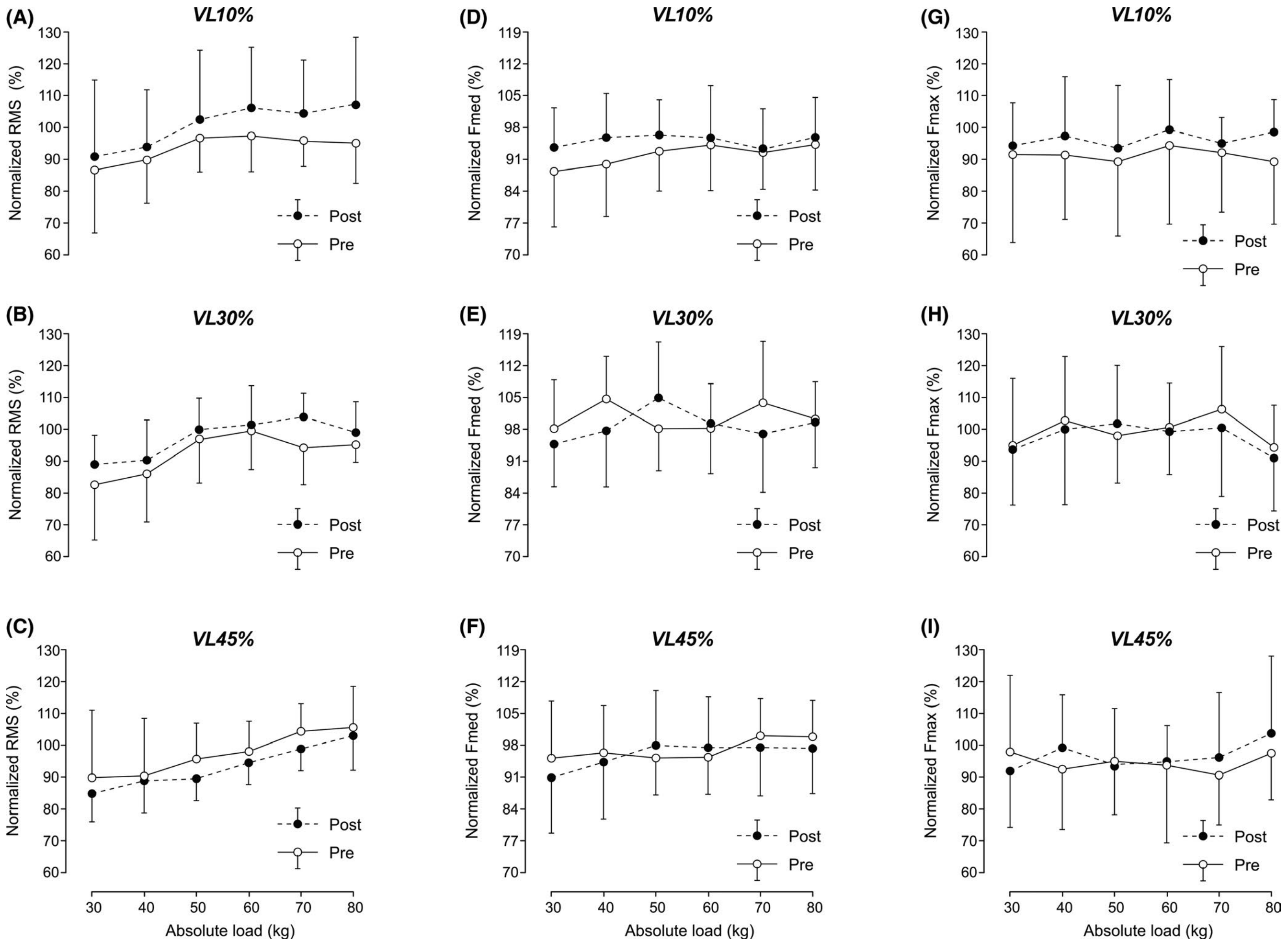

FIGURE 2 Changes in the normalized root mean square (RMS) (A–C), F_{med} (D–F), and F_{max} (G–I) electromyographic (EMG) variables against different absolute loads (30–80 kg) in the full squat exercise for the VL10% (top row), VL30% (middle row), and VL45% (bottom row) groups. Data are mean ± SD

($p < 0.05$–0.001) except in sprint performance, AV>1 (Table 2) and MPV attained against 30, 40, and 50 kg (Figure 1).

3.3 | EMG

No significant "time × group" interactions, between-group and intra-group changes were observed for any EMG variable in any experimental group (Figure 2).

3.4 | Relationships between the individual changes of selected training and performance variables

When data from all groups were pooled, significant correlations were found between the individual relative (percent) changes in CMJ and the individual changes in sprinting ability (T10 and T20, $p < 0.001$) and selected squat strength variables (AV, AV>1, and AV<1, $p < 0.01$–0.05). Changes in T10 and T20 showed moderate and significant relationships with changes in most strength variables ($r = -0.356$ to -0.475; $p < 0.05$–0.01) and changes in performance in the fatigue test ($r = -0.406$ and -0.475, for T10 and T20, respectively). Relative changes in the fatigue test were also correlated with changes in strength variables ($r = 0.364$–0.712; $p < 0.05$–0.001). Moreover, significant correlations were observed between the individual changes in performance variables and mean training velocity and the total number of repetitions completed during the training program (Table 3).

4 | DISCUSSION

The aim of the present study was to compare the effect of three magnitudes of VL in the set (10% vs. 30% vs. 45%) while training using the same loads (55–70% 1RM) in the SQ exercise, on changes in neuromuscular performance. Our main findings were that VL10% resulted in greater improvements in CMJ and sprinting performance, and similar or even greater increments in muscle strength and muscle endurance than VL30% and VL45%, whereas no statistically significant changes were observed in EMG variables for any training group. Therefore, our results seem to suggest that a lower intra-set volume (expressed and monitored, in this case, by the percent VL reached in each set) allows for a more efficient training stimulus, since it yields similar or even greater gains in neuromuscular performance while performing significantly less repetitions and inducing a much lower degree of effort or fatigue (mechanical and physiological stress) compared to higher training volumes that result in higher velocity losses.[14,41,43] Despite the relevance of these results, it is important to note that the current findings may differ in other populations. Thus, further studies are needed to clarify whether the observed effects would be similar in, for instance, older people or highly trained athletes.

The RT program resulted in significant increments in strength variables for all groups, with VL10% and VL30% showing greater pre-post percent changes and ES than VL45% (Table 2 and Figure 1). These differences were especially noteworthy between the VL10% and VL45% groups in AV>1 (Δ: 8.5% vs. 1.9%; ES: 2.14 vs. 0.38) and MPV attained with 30–60 kg (Δ: 6.4–16.4% vs. 1.8–7.6%), despite the fact that VL10% only performed, on average, 36% of the repetitions completed by VL45% (180.8 vs. 501.1). In line with our results, previous studies using a velocity-based RT approach[17,18,23] have also shown the superiority of training with low (VL10% and VL20%) compared to high (VL30% and VL45%) number of repetitions per set in order to improve neuromuscular performance. However, it is important to note that a minimum VL in the set is necessary to obtain gains in muscle strength, since it has been found that performing a single repetition per set (VL0%) is not a sufficient stimulus to obtain significant improvements.[18] In this regard, it appears that magnitudes of VL in the set as low as 5% could be sufficient to induce significant increments in strength performance (Δ: 10.7%; ES: 0.71) in moderately strength-trained subjects.[44] Nevertheless, further studies are needed since the minimum VL useful to induce improvements in physical performance could be different depending on training experience, relative load, the specific training goal, maturity status, chronological age, the particular exercise to be performed, and the performance level of the athlete.

Traditionally, "heavy resistance training" (resistance exercise against loads >75–80% 1RM) has been considered an essential requirement to maximize strength gains, while performing exercise sets to failure has been associated with greater muscle hypertrophy.[6,45,46] In contrast, results of the present study showed that RT using considerably lighter loads of 55–70% 1RM induced similar or even greater strength improvements than heavier loads, similarly to that previously reported.[17,18,23] In addition, and regardless of the relative load used, it appears that performing a lower number of repetitions per set results in an improved neuromuscular function[17,18,23] which translates into actual benefits in high-speed actions such as jumping and sprinting but also, as observed in this study, in an enhanced resistance to fatigue. Interestingly, and supporting this assertion, significant negative correlations were observed between the total number of repetitions completed during the present training program and the percent changes in selected strength performance variables (Table 3). Similarly, relative changes in 1RM, AV, AV>1, and AV<1 were correlated with mean training velocity (Table 3). These results suggest that the lower the number of repetitions per set (low VL) and the higher the average training velocity, the greater the neuromuscular gains.

Regarding the fatigue test, all experimental groups showed significant ($p < 0.01$–0.001) increments in the number of repetitions completed against the ~70% 1RM load used. Although there were no significant differences between groups and the percent changes were very similar (Figure 1D), greater ES were found for VL10% compared to VL30% and VL45% (Table 2). As indicated above, these results are especially relevant since VL10% (~11.3 reps) completed 10 and 20 total repetitions per session less than VL30% (~21.7 reps) and VL45% (~31.3 reps), respectively. Thus, our results disagree with previous reviews[6,46] which indicated that performing a greater number of repetitions per set during RT maximizes gains in local muscular endurance. In this line, previous studies comparing RT programs with different numbers of repetitions[16,47] or VL within the set[17,18] also showed no significant differences between groups in local muscular endurance. Taken together, results of these studies suggest that the increments observed in the number of repetitions completed against a given absolute load do not directly depend on the number of repetitions performed in each training set, which agrees with the low and non-significant correlations found in the present study between the individual relative changes in the fatigue test and the total number of repetitions completed during the training program ($r = -0.158$) and mean training velocity ($r = 0.144$; Table 3). As indicated in a previous study,[17] increments in muscle endurance against moderate loads (~70% 1RM) seem to be mainly related to the increase in 1RM strength ($r = 0.712$; $p < 0.05$; Table 3). This can be explained by the fact that, as the participants improved their 1RM, the absolute load (kg) used during the fatigue test at Post represented a lower relative load (%1RM), which allowed them to complete a greater number of repetitions.[13] However, further studies are needed to clarify the extent to which the improvements in maximal strength (1RM) are associated with increases in muscle endurance against light loads.

Changes in physical performance were progressively lower as the VL increased, with VL10% showing significantly greater percent change and ES in CMJ (Δ: 11.9%; ES: 0.75) and sprint times (Δ: −2.4 to −3.1%; ES: −0.80 to −0.89) than VL30% and VL45% (Table 2 and Figure 1).

Thus, it was observed that despite similar changes (Δ: 15.4–22.2%) in maximum strength (1RM), the degree of transfer to actual physical performance was dependent on the magnitude of VL attained in the set, suggesting that the training effect on jumping and sprinting is not only determined by the relative load used but especially by the degree of fatigue incurred in each set. In this regard, the information contained in Table S2 is particularly revealing when trying to ascertain the observed adaptations. Even though the groups trained at a significantly different average velocity (0.91, 0.83, and 0.76 $m \cdot s^{-1}$ for VL10%, VL30%, and VL45%, respectively), there were no differences between groups in the number of repetitions performed at high velocities (>0.90 $m \cdot s^{-1}$), whereas the number of repetitions performed at slower velocities (< 0.90 $m \cdot s^{-1}$) was progressively greater as VL increased, showing significant differences between VL10%, VL30%, and VL45% (Table S2). In other words, it is not that the VL30% and VL45% groups did not perform repetitions at high velocities, but that they performed a much greater number of slow repetitions (the greater as the higher was the VL incurred in each set). So, it could be argued that it is not a lack of fast repetitions performed during training but an excessive amount of fatigue that interferes in the adaptation process and precludes participants in groups VL30% and, especially VL45%, to obtain optimal adaptations directed toward rapid force production. As a plausible hypothesis, it is likely that the greater number of very slow repetitions (< 0.70 $m \cdot s^{-1}$) performed by the VL45% group could elicit a remodeling in muscle phenotype with IIX to IIA fiber type transformations, as found in a similar study which compared VL20% and VL40%.[23] This fact, along with the absence of changes in the EMG variables, could be a major physiological factor responsible for the lower improvements in jumping and sprinting performance obtained by VL45% compared to VL10%.

In line with the present findings, previous studies[17,18,44] comparing different magnitudes of VL allowed during RT using the SQ exercise have shown that a VL in the set around 5–10%, performed against the same relative load, resulted in more beneficial effects on jumping and sprinting performance compared to greater percentages of VL. Indeed, previous research suggests that exceeding a certain VL limit (~20%) within the set could lead to performing unnecessarily slow and fatiguing repetitions which end up inducing a performance loss in running sprint ability.[17,23] According to these results, it has also been recently observed that a VL in the set around 10% during resisted sled towing training against moderate-to-heavy loads (45–65% of body mass) resulted in greater beneficial effects on sprint performance (T10 and T20) compared to a 20% VL.[48] As suggested, the changes in CMJ and sprinting performance may be related to the principle of specificity.[17,49] In this regard, the significant correlations found in the present study between mean training velocity and changes in CMJ, T10, and T20 (Table 3) appear to confirm the importance of actual repetition velocity as a key variable in determining the adaptations necessary for improving performance in high-speed actions such as vertical jumping and sprinting ability.[17]

In addition to analyzing changes in physical performance, another objective of the present study was to try to shed some light on the physiological factors underlying the observed neuromuscular adaptations. Interestingly, the greater improvements in strength, jumping, and sprinting performance experienced by the VL10% group were accompanied by a slight, although not statistically significant, increase in neural activation (RMS, $F_{med,}$ and F_{max}) of the agonist musculature involved in the SQ exercise. Conversely, EMG variables remained unchanged for VL30% and VL45% (Figure 2). These results are in agreement with a previous study[17] and suggest that the changes in strength and functional performance obtained by each experimental group could perhaps be the consequence of different neuromuscular adaptations. Whereas the improvements in maximum strength (1RM), MPV attained against different absolute loads and jumping and sprinting performance observed in VL10% could be related, at least partially, to changes in neural adaptations,[16–18,22] changes showed by VL30% and VL45% could be mainly due to structural adaptations. This could be due to the fact that RT with greater VL in the set produces greater mechanical, metabolic, and hormonal stress,[20,21,50] which are factors mediating hypertrophic adaptations.[51] In this regard, previous studies have shown that moderate-to-high magnitudes of VL in the set (>20%) are accompanied by significant muscle hypertrophy and increase in fascicle length and pennation angle, whereas low magnitudes of VL in the set (≤10%) appear to be insufficient to induce changes in these structural factors.[18,22,23]

In conclusion, our main findings were that VL10% resulted in greater improvements in CMJ and sprinting performance, and similar or even greater increments in muscle strength and muscle endurance than VL30% and VL45%. In addition, although no statistically significant differences were observed in EMG variables for any training group, only VL10% showed slight increments in RMS, $F_{med,}$ and F_{max} variables. Therefore, our results seem to suggest that establishing a low percent VL limit (10%) during each exercise set allows for a very effective and more efficient training stimulus, since it yields similar or even greater gains in neuromuscular performance while performing significantly less repetitions and inducing a much lower degree of fatigue (mechanical and physiological stress) compared to higher training volumes that incur in higher velocity losses.

4.1 | Limitations

Despite the observed findings, it is important to clarify that our study presents some limitations that might have influenced the observed physiological changes and its consequent interpretation, mainly with regard to the EMG variables. In the present study, only the changes in surface EMG of V_{LA} and V_{ME} were analyzed. However, it is obvious that many other muscles contributing to leg extension during the SQ exercise were not assessed. Thus, it would not be appropriate to assert that the gains in strength and jumping ability in VL30% and VL45% were not due or related to changes in electrical muscle activity. Another possible limitation of this study is related to the difficulty of interpreting surface EMG during dynamic contractions. In this regard, different factors including (a) the dynamic nature of the task studied (SQ exercise); (b) the changes in electrode placement with respect to the muscle's fiber orientation due to changes in joint angle; (c) the alteration in the conductivity of the tissues as a consequence of changes in muscle fiber diameter, length, and orientation that occurs during a dynamic contraction may affect the stationarity of the EMG signals and interfere in the recorded EMG signal, invalidating the use of the Fourier transform to calculate the power spectrum variables.[52–55] On the other hand, neural adaptations are very specific to the conditions in which they are acquired.[56,57] Thus, caution should be taken in determining the influence of neural adaptations measured during the SQ exercise on changes in jumping and sprinting ability. Finally, as indicated above, the findings of the present study are limited to the population analyzed, and the specific training program performed.

5 | PERSPECTIVE

One of the key steps for designing an effective RT program is the appropriate selection of the variables that determine the training stimulus, mainly the load (% 1RM) and the magnitude of VL to be allowed in each training set. Deciding on the values of these two variables must take into account the initial situation and performance level of the athlete as well as the strength requirements of his or her sport. Based on the present findings and those of previous research,[17,18,23] coaches and strength and conditioning professionals should consider using magnitudes of VL in the set as low as 10% in the design of RT programs aimed at improving physical performance, since these have proven greatly effective for obtaining considerable strength gains and positive lower-body strength transfer to actual high-speed actions such as jumping and sprinting. In addition to the benefits on neuromuscular performance, these lower velocity losses reached in the exercise sets are associated with a much lower degree of fatigue and faster recovery times,[14,41,50] which could help individuals to better cope with the overall training load. Taken together, the results of the present study contribute to an increasing body of recent research (performed with an unprecedented level of control over the training variables) that challenges the traditional heavy-resistance, greatly fatiguing, strength training "dogma". It is perhaps timely to redefine the existing RT paradigm toward more rational and efficient methods aimed at improving muscle strength and neuromuscular performance.

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CONFLICTS OF INTEREST

The authors have no conflicts of interest to disclose between any outside institution, company, or manufacturer. The results of this study are presented clearly, honestly, and without fabrication, or inappropriate data manipulation.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

David Rodríguez-Rosell https://orcid.org/0000-0002-6263-9470

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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